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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

A brief overview and summary of results obtained in the development, analysis, and testing of approximation theory and techniques for the identification and control of distributed parameter systems is provided. The research carried out under this grant can be classified into seven sub-headings. These include 1) the identification of nonlinear distributed parameter systems, 2) the identification and control of thermoelastic systems, 3) the identification and control of degenerate distributed parameter systems, 4) discrete-time linear quadratic control of distributed parameter systems, 5) optimal LQG control of discrete time parabolic systems, 6) optimal fixed finite order compensators for infinite dimensional systems, and 7) convergence of Galerkin approximations to operator Riccati equations. Our results in each of these areas is described separately and in turn.

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Final Report for

# Approximation Methods for the Identification and Control of Distributed Parameter Systems with Applications to Flexible Structures

Air Force grant AFOSR - 87 - 0356

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## 1. Research Summary

Our research over the course of the reporting period 1 October, 1987 through 31 October, 1990 has been focused on the development, analysis, and testing of approximation techniques for the identification and control of distributed parameter systems. Our results have been described in detail in the 21 research papers that carry the above grant number and which have been supplied to the AFOSR Mathematical and Information Sciences Directorate via the control theory program manager. In this report we provide a brief overview of our findings and results. Our summary will be divided into subsections, each one dealing with a particular research area that we have dealt with during the reporting period. We have included a complete list of the papers we have written which carry this grant number, and we also provide a list of graduate students who have been supported under this grant and the titles of their theses. Finally we list meetings that we have attended and papers that we have presented during this reporting period.

**1.1 The Identification of Nonlinear Distributed Parameter Systems:** We have developed an abstract approximation framework for the identification of infinite dimensional nonlinear control systems. Convergence results are obtained via nonlinear functional analytic techniques (e.g. the theory of monotone operators in Hilbert space) and are applicable to a wide class of first (both autonomous and non-autonomous, i.e. systems with dynamics described by time varying nonlinear operators) and second order systems. We have considered examples involving the identification of both a time invariant and a temporally varying nonlinear generalization of Fourier's law of heat conduction and the identification of nonlinear dissipation mechanisms (i.e. damping) in a wave equation.

Numerical studies have been carried out on the Cray X/MP-48 at the San Diego Supercomputer Center. Our schemes were observed to perform well in virtually every test example that we considered. This was joint work with Professor H. T. Banks, formerly of The Center for Control Sciences in the Division of Applied Mathematics at Brown University and currently director of The Center for Applied Mathematical Sciences in the Department of Mathematics, University of Southern California, Professor Simeon Reich of the Department of Mathematics, University of Southern California, and a Master's student, Calvin Lo. Our thoretical results for autonomous first order systems were reported on in a paper which has appeared in the SIAM Journal on Control and Optimization. The theory and numerical studies for time varying first order systems are reported on in a paper which has been accepted for publication in the Journal of Applied Mathematics and Optimization. The theory for second order systems is contained in a paper which has appeared in Control-Theory and Advanced Technology. A summary of

our numerical findings for both autonomous first, and second order systems is contained in a paper which has appeared in the proceedings of the 4th International Conference on the Control and Identification of Distributed Parameter Systems held in Vorau, Austria in July, 1988.

**1.2 Identification and Control of Thermoelastic Systems:** We have developed and studied the approximation theory for the optimal linear - quadratic Gaussian control and estimation of linear thermoelastic systems. These systems consist of a coupled second order equation of elasticity and the first order heat equation. In general, the presence of the heat dissipation provides extremely light damping for the mechanical system. Consequently, if no other damping is present, control design can be difficult. Of particular interest to us has been the question of how thermoelastic damping affects control design in both the presence and absence of other forms of mechanical dissipation; for example, Kelvin-Voigt or structural damping. We have been especially interested in looking at the subsequent performance of a control law designed without regard to thermoelastic effects. For example, could instability result, or are thermoelastic effects so small that they can be disregarded in control synthesis. Also, we have found that the control law and estimator designed by replacing the thermoelastic system by a modal model for a second order system with the same amount of damping on each mechanical mode as is supplied via the heat dissipation, are virtually identical to the ones obtained using the thermoelastic system directly. This shows that the optimal control law and state estimator can be obtained at a greatly reduced level of computation. This was joint work with Professor J. S. Gibson of the Department of Mechanical, Aerospace, and Nuclear Engineering at UCLA, and a former student of mine, Mr. Gang Tao, presently in the Department of Electrical Engineering at Washington State University in Pullman, Washington.

A paper detailing some of our preliminary results dealing with approximation has appeared in the Proceedings of the 1989 American Control Conference (ACC) which was held in Pittsburgh in June, 1989. Some further results were reported on in a paper which is to appear in the Proceedings of the NASA/NSF/DOD 3rd Annual Conference on Aerospace Computational Control, which was held in Oxnard, California, in August, 1989. A journal paper which carefully details both our theoretical and numerical findings has been submitted for consideration for publication in the SIAM Journal on Control and Optimization.

We have also investigated the identification of linear thermoelastic systems. Our primary focus here has been approximation, and we are again especially interested in the interplay between thermoelastic damping and other forms of dissipation. This is

joint work with a former student, Mr. Frank Su. Both our theoretical and numerical studies have been reported on in a paper which has been accepted for publication in the Journal of Differential and Integral Equations. In this paper we have included a report on our investigations into our ability to discern between various forms of dissipation from observational data.

We intend to turn our attention next to the identification of nonlinear thermoelastic effects. In particular, this would include the identification of temperature dependent material parameters, or properties, in the governing partial differential equations of elasticity. It is in these studies that we hope to use the experimental data collected for us by Dr. Alok Das at the Air Force Astronautical Laboratory (AFAL) at Edwards Air Force Base here in California.

**1.3 The Identification and Control of Degenerate Distributed Parameter Systems:** We have developed an abstract approximation framework for the identification of degenerate linear distributed parameter systems. By a degenerate system we mean one in which the operator coefficient of the term involving the highest order derivative does not have a bounded inverse. Our approach required that we establish a version of the well-known Trotter-Kato approximation result for linear semigroups which is applicable to either regular or degenerate implicit systems. As one might guess the resolvent convergence condition is replaced by a similar one involving the generalized inverse. We have considered both first and second order systems and have now turned our attention to second order and nonlinear first and second order systems. Once again numerical studies were and are being carried out on the Cray in San Diego. The linear theory is joint with Professor P. K. Lamm of the Department of Mathematics, Michigan State University and the University of North Carolina, the numerical studies were carried out jointly with Professor Lamm and a student, Calvin Lo, while the nonlinear theory and numerical studies for both first and second order systems is the subject of my student, Chao Lin Mao's Ph.D. dissertation research.

A brief outline of our results to date are contained in a paper which has appeared in the proceedings of the IFAC meeting on the control and identification of distributed parameter systems which was held in Perpignan, France in June, 1989. A paper detailing our theory and numerical findings for the linear problem has been accepted for publication in The Journal of Mathematical Analysis and Application. Theoretical and numerical studies for linear second order systems, and nonlinear systems are currently on-going. We have also started to investigate the application of our approximation theory for degenerate systems in the context of continuous and discrete or sampled time linear-quadratic control for certain classes of infinite dimensional descriptor variable systems.

Our numerical studies for the linear problem pointed to a need to develop finite element or generalized Galerkin schemes either of hybrid type, or using non-conforming elements. We have done this and have reported our findings in a paper which has been submitted for consideration for publication in the Proceedings of the Fifth International Conference on the Identification and Control of Distributed Parameter Systems held in Vorau, Austria, July 9-13, 1990. This work was carried out jointly with my student, Ms. Poornima Raghu.

**1.4 Discrete-Time Linear Quadratic Control of Distributed Parameter Systems:** We have investigated the convergence of the solutions to the discrete-time operator Riccati differential and algebraic equations to the solutions of the corresponding continuous time equations as the length of the sampling interval tends toward zero. That is, we have studied the continuous dependence with respect to sampling of the infinte dimensional linear quadratic regulator problem on both the finite and infinite time horizon, and the solutions to the corresponding associated operator Riccati equations. Not surprisingly this investigation required that we also consider the relationship between discrete and continuous time system theoretic concepts such as controllability, observability, stabilizability, and detectability. We have found that a sufficient condition for convergence is stabilizability and detectability, uniformly with respect to the sampling rate. Moreover, we found that this could be guaranteed when the continuous time system is stabilizable and detectable via finite rank feedback. In addition, we found that this condition could be readily verified in the case of parabolic systems. We have carried out numerical studies involving the control of a one dimensional heat equation, a one dimensional hereditary (delay) system, and the transverse vibration of a cantilevered Voigt-Kelvin viscoelastic beam with tip mass. This is joint work with Professor Chunming Wang of the Department of Mathematics, University of Southern California. A brief outline of our results have appeared in the Proceedings of the 1989 and 1990 IEEE Conference on Decision and Control (CDC), and a paper containing all of the details of both our theoretical and numerical studies has been accepted for publication in the SIAM Journal on Control and Optimization. Our results on questions of stabilizability and detectability and their relation to sampling are reported in a paper which has been submitted to the IEEE Transactions on Automatic Control.

**1.5 Optimal LQG Control of Discrete-Time Parabolic Systems:** We have developed an abstract approximation and convergence theory for the closed-loop solution of discrete-time linear-quadratic regulator problems for parabolic systems with unbounded input. Under relatively mild stabilizability and detectability assumptions, together with

the usual Galerkin approximation condition (i.e. strong V-norm convergence to the identity of the orthogonal projections), using functional analytic operator theoretic techniques we were able to demonstrate norm convergence of Galerkin-based approximations to the optimal feedback control gains. The general theory we developed can be applied to a broad class of boundary control systems. These include the Neumann boundary control of the heat/diffusion equation, and the shear or bending moment boundary control of a cantilevered beam with Voigt - Kelvin viscoelastic damping. These results were reported on in a paper which has appeared in Control-Theory and Advanced Technology.

**1.6 Optimal Fixed Finite Order Compensators for Infinite Dimensional Systems:** In conjunction with Dr. D. S. Bernstein of the Harris Corporation we have developed a finite dimensional approximation theory for the Bernstein/Hyland optimal projection approach to computing optimal fixed finite order compensators for distributed parameter systems. The technique has been tested and shown to perform well on one dimensional single input/single output parabolic (i.e heat/ diffusion equations) and hereditary control systems. Our results were reported on in a paper which appeared in the proceedings of the 1988 IEEE Conference on Decision and Control (CDC) and in a paper which has appeared in the journal Optimal Control - Applications and Methods. We are planning to continue both our numerical and our theoretical investigations in this area. In particular, we hope to be able to develop an abstract convergence theory such as has been done for the LQG regulator problem, to extend our results to the discrete or sampled time problem, and to apply our theory to a wider class of test examples. The examples we consider would include the control of some type of flexible structure, i. e. a beam or plate.

**1.7 Convergence of Galerkin Approximations to Operator Riccati Equations:** We have studied the convergence of Galerkin approximations for solutions to operator Riccati differential equations. Our treatment is based upon a formulation of the Riccati equation as a nonlinear abstract evolution equation in the space of Hilbert - Schmidt operators on a separable Hilbert space. We were able to demonstate the Hilbert - Schmidt norm convergence of the solutions to a sequence of approximating nonlinear Galerkin equations to the solution to the original infinite dimensional operator equation. We were also able to develop a similar approximation and convergence theory for operator algebraic Riccati equations. These results were reported on in a paper which has appeared in the Proceedings of the Fourth International Conference on the Identification and Control of Distributed Parameter Systems held in Vorau, Austria in July, 1988, and in a paper which has been accepted for publication in the Journal of Mathematical Analysis

and Applications.

## 2. Papers Which Carry This Grant Number

1. An Approximation Theory for the Identifcation of Nonlinear Distributed Parameter Systems (with H.T. Banks and S. Reich), SIAM J. Control and Opt., **28** (1990), pp. 552-569.

2. Galerkin Approximation for Inverse Problems for Nonautonomous Nonlinear Distributed Parameter Systems (with H.T. Banks and S. Reich), Applied Mathematics and Optimization, to appear.

3. Finite Dimensional Approximation for Optimal Fixed-Order Compensation of Distributed Parameter Systems (with D.S. Bernstein), Optimal Control, Applications and Methods, **11** (1990), pp. 1-20.

4. An Approximation Technique for Computing Optimal Fixed-Oreder Controllers for Infinite Dimensional Systems (with D.S. Bernstein), Proceedings of 27th IEEE Conference on Decision and Control, Austin, Texas, December 7-9, 1988, pp. 2023-2028.

5. Optimal Discrete-Time LQR Problems for Parabolic Systems with Unbounded Input-Approximation and Convergence Control-Theory and Advanced Technology, **5** (1989), pp. 277-300.

6. Parameter Estimation in Nonlinear Distributed Systems - Approximation Theory and Convergence Results (with H.T. Banks and S. Reich), Applied Mathematics Letters, **1** (1988), pp. 211-216.

7. Convergence of Galerkin Approximations for Operator Riccati Equations - A Nonlinear Evolution Equation Approach, J. Math. Anal. and Applic., to appear.

8. On Hilbert-Schmidt Norm Convergence of Galerkin Approximations for Operator Riccati Equations, Proceedings of 4th International Conference on the Identification and Control of Distributed Parameter Systems, Vorau, Austria, July 10-16, 1988, Birkhäuser, 1989, pp. 335-349.

9. Numerical Studies of Identification in Nonlinear Distributed Parameter Systems (with H.T. Banks, C. Lo and S. Reich), Proceedings of the 4th International Conference on the Control and Idenficiation of Distributed Parameter Systems, Vorau, Austria, July 10-16, 1988, Birkhäuser, 1989, pp. 1-20.

10. Estimation of Nonlinear Damping in Second Order Distributed Parameter Systems (with H.T. Banks and S. Reich), Control-Theory and Advanced Technology, 6 (1990), pp. 395-416.

11. Identification of Degenerate Distributed Parameter Systems (with P. Lamm and C. Lo), Proceedings 5th IFAC Conference on Control of Distributed Parameter Systems, June 26-29, 1989, Perpignan, France, pp. 347-352.

12. An Approximation Theory for the Estimation of Parameters in Degenerate Cauchy Problems (with P. Lamm), J. Math. Anal. Applic., to appear.

13. Convergence of Infinite Dimensional Sampled LQR Problems: Theory and Numerical Results (with C. Wang), Proceedings 28th IEEE Conference on Decision and Control, December 13-15, 1989, Tampa, Florida, pp. 162-167.

14. Approximation in Control of Thermoelastic Systems (with J.S. Gibson and G. Tao), Proceedings of 1989 IEEE Americal Control Conference, June 21-23, 1989, Pittsburgh, PA.

15. On the Continuous Dependence with Respect to Sampling of the Linear Quadratic Regulator Problem for Distributed Parameter Systems (with C. Wang), SIAM J. Control Opt., to appear.

16. Approximation in the Optimal Control of a Thermoelastic Rod (with J.S. Gibson and G. Tao), Proceedings of NASA/NSF/DOD 3rd Annual Conference on Aerospace Computational Control, Oxnard, CA, August 1989.

17. An Approximation Theory for the Identificiation of Linear Systems (with F. Su), Differential And Integral Equations, to appear.

18. Approximation in Control of Thermoelastic Systems (with J.S. Gibson and G. Tao), SIAM J. Control Opt., submitted.

19. On Stabilizability and Sampling for Infinite Dimensional Systems (with C. Wang), IEEE Transactions on Automatic Control, submitted.

20. Finite Rank Stabilizability and Perservation of Stabilizability under Sampling for Distributed Parameter Systems (with C. Wang), Proceedings 29th IEEE Conference on Decision and Control, Honolulu, HI, December 5-7, 1990, pp. 375-376.

21. Approximation in the Identification of Degenerate Distributed Parameter Systems: Generalized Galerkin Schemes and nonconforming Elements (with P. Raghu), Proceedings 5th International Conference on Control and Identification of Distributed Parameter Systems, Vorau, Austria, July 9-13, 1990, submitted.

## 3. Graduate Students Whose Projects Were Supported By This Grant

1. R. Csipke - The Identification of time varying parameters in a distributed model for biological mixing in deep-sea sediment cores. (M.Sc. 1990)
2. C.K. Lo - An implementation of a computational technique for the identification of nonlinear distributed parameter systems. (M.Sc. 1988)
3. C. Mao - Approximation in the identification of nonlinear degenerate distributed parameter systems. (Ph.D. 1991)
4. P.C. Raghu - Approximation in the identification of degenerate distributed parameter systems. (M.Sc. 1991)
5. F. Su - A Ritz-Galerkin method for the identification of linear thermoelastic systems. (M.Sc. 1989)
6. G. Tao - Approximation in control of thermoelastic systems. (M.Sc. 1989)

## 4. Professional Meetings and Conferences Attended and Papers Presented

1. Invited paper, IMACS/IFAC International Symposium on Modelling and Simulation of Distributed Parameter Systems, Hiroshima, Japan, October 6-9,1987.
2. Invited paper and session co-corganizer and co-chairman, 26th IEEE Conference on Decision and Control, Los Angeles, CA, December 9-11, 1987.
3. Invited participant, Workshop on Computational and Experimental Aspects of Control, University of Wisconsin, Madison, May 16-18, 1988.
4. Invited paper, Fourth International Conference on the Control and Identification of Distributed Parameter Systems, Vorau, Austria, July 10-16, 1988.
5. Invited participant and speaker, Workshop on Computational Aspects of Identification and Control of Distributed Parameter Systems, Brown University, Providence, RI, August 11-16, 1988.
6. Invited speaker, Special session on differential and difference equations, AMS Regional meeting, Claremont, CA, Nov. 12 and 13, 1988.
7. Session organizer, chairman, and speaker, 27th IEEE Conference on Decision and Control, Austin, TX, Dec. 7-9, 1988, (Joint paper with D.S. Bernstein).
8. Invited paper, SIAM Conference on Control in the 90's, San Francisco, CA, May 17-19, 1989. (Joint paper with C. Wang, delivered by Wang).
9. Invited paper, 1989 American Control Conference, Pittsburgh, PA, June 21-23, 1989, (Joint paper with J. S. Gibson and G. Tao, delivered by Gibson).
10. Invited paper, Fifth IFAC Symposium on Control of Distributed Parameter Systems, Perpignan, France, June 26-29, 1989, (Joint paper with P. K. Lamm and C. Lo, delivered by Lamm).
11. Invited paper, Third Annual NASA/NSF/DOD Conference on Aerospace Computational Control, Oxnard, CA, Aug 28-29, 1989, (Joint paper with J. S. Gibson and G. Tao, delivered by Gibson).
12. Invited paper, 28th IEEE Conference on Decision and Control, Tampa, FL, December 13 - 15, 1989, (Joint paper with C. Wang, delivered by Wang).

13. Invited paper, Fifth International Conference on the Identification and Control of Distributed Parameter Systems, Vorau, Austria, July 9-13, 1990.

14. Invited papers (2), SIAM Annual Meeting, Chicago, IL. July 16-20, 1990.